APPLICATIONS OF THE MERIS ALGAL PIGMENT PRODUCTS IN BELGIAN WATERS

Kevin Ruddick(1), Youngje Park(1,4), Rosa Astoreca(2), Alberto Borges(3), Geneviève Lacroix(1), Christiane Lancelot(2), Véronique Rousseau(2)

(1) *Management Unit of the North Sea Mathematical Models (MUMM), Royal Belgian Institute for Natural Sciences (RBINS),100 Gulledelle, B-1200 Brussels, Belgium. Email: K.Ruddick{at}mumm.ac.be*

(2) *Ecologie des Systèmes Aquatiques (ESA), Faculté des Sciences, Université Libre de Bruxelles (ULB), Campus Plaine - CP 221, Boulevard du Triomphe, B-1050 Brussels, Belgium.*

(3) *Chemical Oceanography Uni , University of Liège, Institut de Physique (B5), Allée du 6 Août, 17, B-4000 Liège, Belgium*

(4) *Now at CSIRO Land and Water, Environmental Remote Sensing Group, Australia.*

ABSTRACT

Following validation activities and corresponding improvements in processing algorithms over the first few years of the MERIS mission, the algal1 and algal2 products are now considered as sufficiently mature for use in applications in Belgian waters. The utility of this product has been enhanced by the development of a number of multitemporal products including single point time series, multitemporal composites (monthly/3-monthly means) and annual products such as the mean and 90 percentile concentrations and the timing of the spring bloom. Marine management applications include: support for the assessment of eutrophication status in the context of the Oslo and Paris Convention for the Prevention of Marine Pollution (OSPAR), optimisation of seaborne monitoring, detection of harmful algal blooms and support for aquaculture. More generally, the MERIS data is used in support of marine science including the validation of ecosystem models and may be used in the future for the estimation of air-sea carbon fluxes. The current status of these applications is described together with an assessment of the remaining scientific challenges as well as the future possibilities.

1. INTRODUCTION

Since the launch of SeaWiFS in 1997 and, especially MERIS and MODIS in 2002, the usage of ocean colour data for applications in coastal waters has rapidly matured. The accurate retrieval of chlorophyll *a* concentration in turbid coastal waters is challenging because of a) the difficulties in atmospheric correction caused by non-zero near infrared water reflectance [1,2] and b) the high absorption in the blue by non-algal dissolved and particulate matter which masks the absorption signal of phytoplankton. These problems have been partially solved and all three "mainstream" ocean colour sensors, SeaWiFS, MODIS-AQUA and MERIS, are now generating some usable data in turbid coastal waters. However, the MERIS band definition, including the crucial 709nm band for normalization of red chlorophyll *a* absorption, the case 2 water algorithm design and the "Product Confidence" quality control flags provide distinct advantages over the other sensors. The MERIS algal1 and algal2 products are, therefore, considered at present to be the preferred source of satellite chlorophyll *a* related information for Belgian waters.

Of course, before data can be used for applications, validation is necessary. This is particularly important in the case of satellite chlorophyll data in coastal waters because of the aforementioned problems of data processing. Such a validation for the MERIS chlorophyll *a* product in Belgian and Southern North Sea waters is reported in [3]. In general, there is good confidence that the MERIS product detects reliably the spatial and temporal variability of high biomass (e.g. > 3μg/l) algal blooms although the quantitative concentrations may be significantly different from *in situ* concentrations. Lower concentrations can be detected in "case 1" waters where phytoplankton alone determines the water-leaving reflectance. However, the lower concentrations are thought to be unreliable in turbid coastal waters where the high absorption from non-algal dissolved and particulate matter masks the absorption from algal particles, effectively giving a detection limit for satellite chlorophyll *a*. Fortunately for many coastal water applications, it is the high biomass events that are of most interest and so this detection limit is often not a severe constraint.

In addition to the *a posteriori* validation analysis the MERIS algal1 and algal2 products are associated with a pixel-by-pixel Product Confidence (PCD) flag providing some measure of automated quality control.

A general review of applications of optical remote sensing can be found in [4] with examples for the North Sea given in [5]. A technical description of the state of the art of remote sensing of shelf sea ecosystems can be found in [6], with a description of future perspectives. The present paper gives some examples specific to the experience of application of the MERIS algal pigment products in Belgian and North Sea waters.

First the processing of the BELCOLOUR archive of MERIS data for the Southern North Sea is summarized. Then some examples of usage of the MERIS algal pigment products are given for a number of applications. Finally, emerging applications are described and the corresponding developments necessary for serving these applications are outlined.

2. MERIS DATA PROCESSING

The data presented here are based on the standard MERIS chlorophyll *a* (CHL) product as generated by the MERIS Ground Segment processor version MEGS7.4 (equivalent to the "MERIS/5.0" processor). Level 2 data is downloaded daily in near real time from the Data Dissemination System (DDS) Rolling Archive of the European Space Agency. Data prior to June 2006 were downloaded from the MERCI website (http://merci-srv.eo.esa.int/merci), replacing the near real-time data for that period which was generated with an older version of the MEGS processor. Data processing of each image is automated and consists of: cropping, masking of bad or suspect data as denoted by the PCD_17 (algal2) and PCD_15 (algal1) flags, remapping and generation of digital image and graphics files for subsequent multitemporal processing or web site distribution. The algal2 or algal1 product is selected as representing CHL depending on whether the turbid case2 water flag is set or not. Red-Green-Blue composites are also generated from the Level 1 top-of-atmosphere data. All available daily reduced resolution (RR) imagery of the Southern North Sea since the beginning of the ENVISAT mission is organised in the BELCOLOUR image archive. Selected graphical image products are available to authorised MERIS users via the BELCOLOUR web site as illustrated in Figure 1.

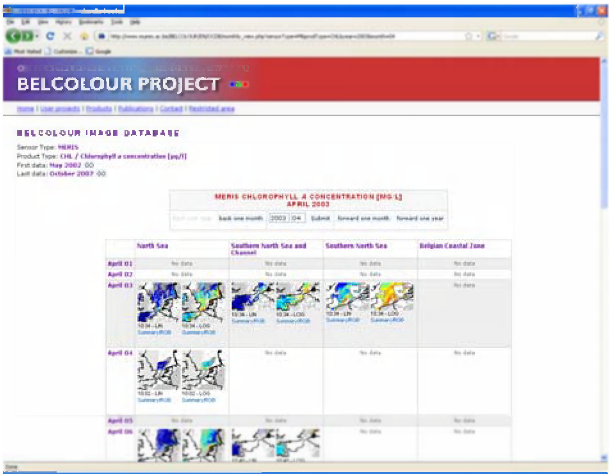

Figure 1. A typical screenshot of the BELCOLOUR web site (http://www.mumm.ac.be/BELCOLOUR).

Further products such as multitemporal composites and extracted time series for specified locations are generated offline on request. Future automated web extraction of some of these products is planned.

3. APPLICATIONS

3.1 Optimisation of seaborne monitoring

In the framework of the Eutrophication Strategy of the Oslo and Paris Convention for the Prevention of Marine Pollution (OSPAR), the Belgian authorities are obliged to perform seaborne monitoring of, *inter alia*, chlorophyll *a* concentration and nutrients. These measurements are reported to OSPAR on a 5-yearly basis in the form of a National Assessment of Eutrophication. The introduction of the European Union's Water Framework Directive (EU-WFD) has expanded greatly the number of parameters for which seaborne monitoring is required in the first nautical mile from the coast and has increased the sampling frequency to monthly. It was necessary to cope with these increased requirements within the existing resource constraints, particularly the human resources for sampling at sea and for chemical analysis. It was decided to redesign the network of stations at which monitoring is performed from the historical network of about 17 open sea and 2 estuarine locations. To remain compliant with the OSPAR Eutrophication Committee requirements, this reduction of locations had to be associated with a justification that the new spatial sampling remained sufficient. Analysis of MERIS imagery (see Figure 3 of [5]) demonstrated that the essential features of the spatial distribution of chlorophyll *a* during the high biomass spring bloom could be captured by a reduced monitoring network of about 9 open sea locations. After consideration of other factors (navigation, needs for sampling other parameters, avoidance of areas with usage conflict, etc.) a new network was designed for monitoring of chlorophyll *a* allowing a reduction from 17 to 10 of open sea sampling locations (Figure 2).

3.2 Eutrophication monitoring

In addition to the optimisation of seaborne monitoring, satellite chlorophyll imagery can be used directly to supplement *in situ* measurements, providing excellent spatial and good temporal coverage. For states with long coastlines satellite imagery becomes particularly attractive as a low cost supplement to a sparse network of *in situ* monitoring locations. Satellite monitoring of eutrophication for the purposes of fulfilling reporting obligations to OSPAR and/or the EU-WFD is under consideration or already in progress for a number of North Sea states including the UK, France, Belgium and Spain. The OSPAR and EU-WFD requirements have led to the development of multitemporal percentile 90 (P90) chlorophyll *a* products [7]. A P90 product for the entire OSPAR area is given in Figure 3.

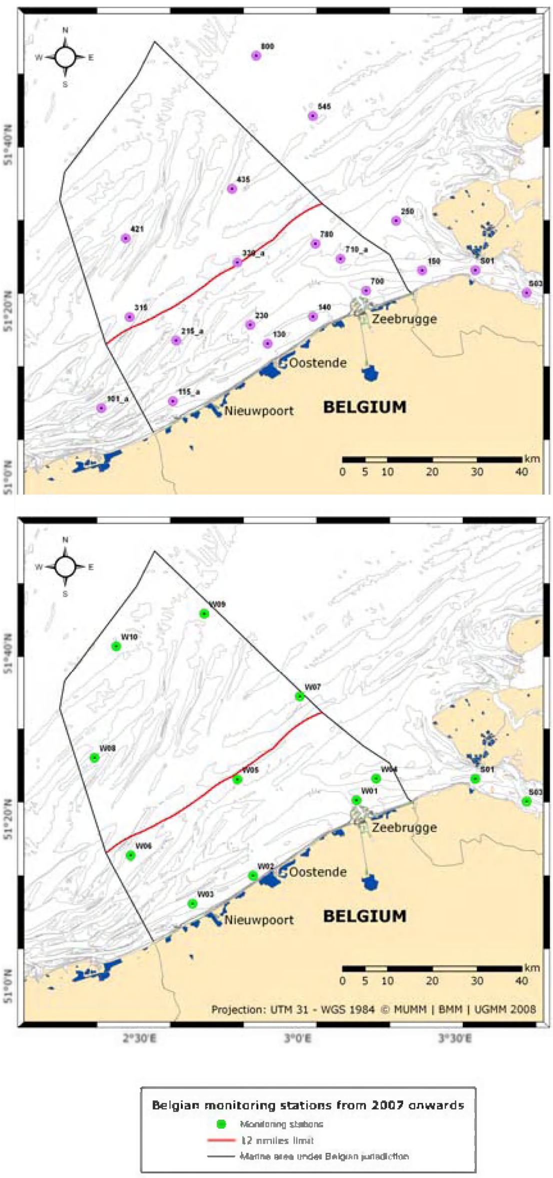

Figure 2. Location of the seaborne measurement stations of the Belgian water quality monitoring network (top) before 2007 and (bottom) after optimisation for EU-WFD and OSPAR requirements. [courtesy of the Belgian Marine Data Centre, http://www.mumm.ac.be/datacentre/]

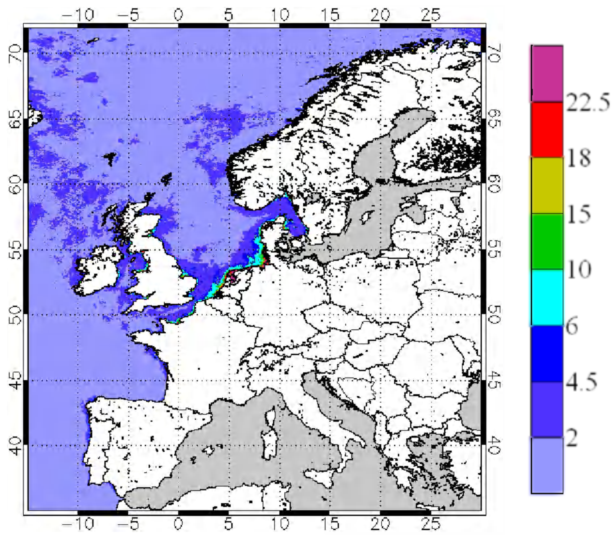

Figure 3. Chlorophyll a P90 derived from MERIS data for the 2005 growing season (March-October). The non-linear colour scale corresponds to various eutrophication problem thresholds used by the OSPAR member states.

3.3 Harmful Algae Bloom detection

Satellite detection of Harmful Algae Blooms (HAB) is required in many regions where toxic or otherwise harmful algae may impact on economic resources such as fisheries, aquaculture or tourism [8]. The limitations of satellite HAB detection are described in detail in [9]. For example, satellite data a) generally gives information only on algae biomass and not on harmfulness, b) is available only in cloud-free periods, c) only gives information on near-surface blooms. Despite these limitations, satellite chlorophyll information can be very useful for (H)AB detection, where the harmfulness is related to the high biomass, as is the case for *Phaeocystis globosa* in Belgian waters [10], or where the HAB species dominates the phytoplankton community. In general the satellite data will be combined with some *in situ* data. AB alert systems are now routinely available for most North Sea waters, e.g. within the MARCOAST project – see section 2.1 of [5].

3.4 Aquaculture

Mussel culture has been introduced recently in Belgian waters on an experimental basis with a view to future expansion and commercialisation. During this experimental stage scientists of the Institute for Agricultural and Fisheries Research (ILVO) of the Flemish government are investigating how mussel yield at different offshore locations can be related to environmental factors. One factor thought to be relevant is the availability of food for mussel growth, which may be related to chlorophyll *a* concentration. Time series information derived from satellite chlorophyll data is being used to analyse mussel yields for the experimental sites – Figure 4. A similar analysis of satellite chlorophyll data in French waters [F. Gohin, Private Communication] was used to choose the optimal location for aquaculture sites. In the case of Belgian waters, the relationship between chlorophyll *a* and mussel yield could be more complex because it is not clear whether the high biomass blooms of *Phaeocystis globosa* are beneficial (palatable) or detrimental to mussel culture.

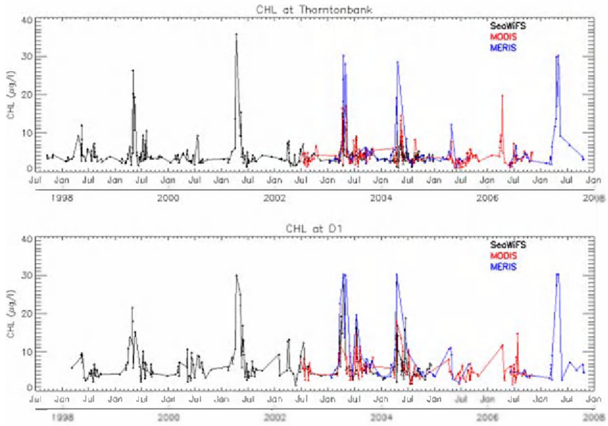

Figure 4 Time series of satellite chlorophyll a data at the location of two experimental mussel farms. Data supplied for an assessment of spatial variation of mussel growth.

3.5 Ecosystem model validation

3D ecosystem models are being used in many North Sea states [11] to assess the impact of anthropogenic nutrient discharges on phytoplankton development. Within the OSPAR framework these models are seen as a management support tool, providing information on the likely impact of nutrient-reduction policies. The Belgian MIRO&CO-3D model [12, 13] has been validated using *in situ* chlorophyll *a* and nutrient data and satellite chlorophyll *a* data. The satellite chlorophyll *a* data revealed – see Figure 7 of [13] – a weakness in the model representation of phytoplankton along the South-East coast of England that has stimulated subsequent model improvements.

3.6 Air-sea carbon flux

The flux of CO_2 across the air-sea interface is an important element of global climate change models. The increase in ocean acidity related to an increase in CO_2 dissolved in seawater poses a threat to the existence of certain marine organisms. *In situ* measurements [14] and modelling [15] are in progress to quantify air-sea CO_2 fluxes at the scale of the Belgian continental shelf and the Southern North Sea. To complement these studies, algorithms are being developed to use a) satellite chlorophyll *a* data, b) satellite Sea Surface Temperature (SST) and c) modelled/climatological sea surface salinity (SSS) distributions to generate maps of partial pressure of CO_2 (pCO_2) and air-CO_2 fluxes.

In the open ocean this approach has to some extent been successful, but greater challenges are expected in coastal waters with more complex optical properties and higher temporal and spatial variability of pCO_2. In the BELCOLOUR-2 project a multi-polynomial-regression (MPR) has been developed, and *in situ* measurements of pCO_2 have been compared with pCO_2 computed by this algorithm from *in situ* SST, chlorophyll *a* and SSS (Figure 5). The correlation achieved is within the range of algorithms developed for pCO_2 in other coastal areas [16, 17, 18]. The next step is to apply this algorithm to satellite data to give, in cloud-free periods, daily maps of pCO_2 for the Southern North Sea.

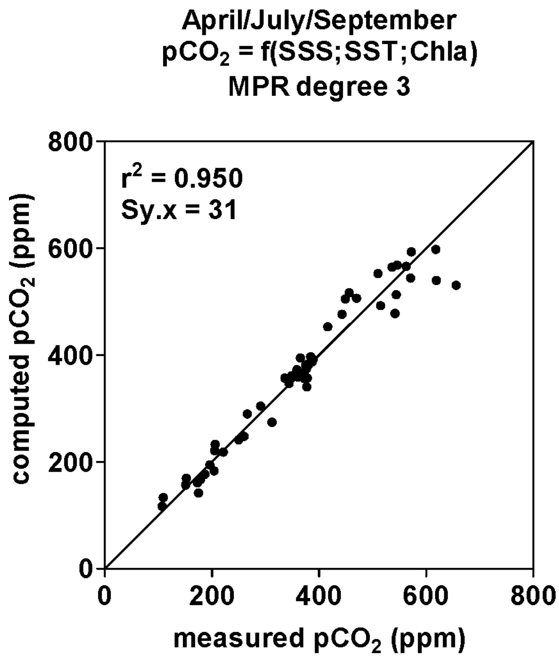

Figure 5. Comparison of pCO_2 as measured in situ and as computed from a third degree multiple polynomial regression using in situ chlorophyll a, SSS, and SST input for 3 cruises (April, July, September 2007) in Belgian waters. Sy.x is the standard error of the linear regression.

In a related study [19] where dissolved organic carbon (DIC) data was used to deduce net ecosystem production in Belgian waters, satellite chlorophyll *a* data was used to explain the observed temporal variability in DIC and pCO_2.

3.7 Other applications

Chlorophyll *a* concentration is a standard parameter in marine biology and hence satellite chlorophyll data is useful as support for many studies in marine biology either to provide a spatial context for observations at discrete locations or to provide time series information.

Chlorophyll *a* maps are now sent to the Research Vessel *Belgica* on request for relevant cruises. This near real-time information allows cruises to be optimised and provides a focus for onboard discussion of *in situ* measurements.

The timing of the spring algae bloom may be useful for fish stock management since early spring diatom blooms determine food availability at the fish larval development stage [20]. A new AB timing product has been developed for such purposes [21].

Marine mammal distributions are known to be related to environmental conditions, particularly those relating to food availability. Now that acoustic techniques are improving information on spatio-temporal distributions there is a growing interest in the use of satellite chlorophyll and SST imagery and water depth information to explain such distributions [22]. Although not a major application in economic terms, this is typical of the many uses to which satellite chlorophyll data can be put, once it is easily available in the form of publicly available web-based archives.

4. CONCLUSIONS AND FUTURE PERSPECTIVES

The MERIS algal pigment index product is becoming established as a source of information for a variety of chlorophyll-related applications in Belgian and North Sea waters. The most mature of these applications are related to national obligations relating to the OSPAR Eutrophication Strategy, where MERIS imagery helped optimise the *in situ* monitoring network by determining the spatial sampling density necessary for reporting to OSPAR. percentile 90 multitemporal chlorophyll *a* products are becoming useful to supplement the *in situ* monitoring for OSPAR and the EU Water Framework Directive and to validate ecosystem models used to simulate OSPAR nutrient reduction scenarios. High biomass surface Harmful Algae Blooms can be detected by MERIS in near real-time. The MERIS imagery is also relevant for a number of scientific studies including mussel growth assessment and research into benthic fauna, for which mortality of pelagic phytoplankton provides a food source. Further applications are under investigation including the mapping of pCO_2 and hence air-sea carbon fluxes.

5. ACKNOWLEDGEMENTS

This study was funded by the Belgian Science Policy Office's STEREO programme in the framework of the BELCOLOUR projects SR/00/03 and SR/00/104. MERIS data was supplied by the European Space Agency under Envisat AOID3443. Daily chlorophyll *a* data for Figure 3 was received from ACRI-ST in the framework of the GMES/MARCOAST project.

6. REFERENCES

[1] Moore, G. F., J. Aiken, and S. J. Lavender. (1999). The atmospheric correction of water colour and the quantitative retrieval of suspended particulate matter in Case II waters: application to MERIS. International Journal of Remote Sensing **20:** 1713-1734.

[2] Ruddick, K. G., F. Ovidio, and M. Rijkeboer. (2000). Atmospheric correction of SeaWiFS imagery for turbid coastal and inland waters. Applied Optics **39:** 897-912.

[3] Ruddick, K.G., Y. Park, R. Astoreca, G. Neukermans, B. Van Mol, 2008. Validation of MERIS water products in the Southern North Sea 2002-2008. ESA Special Publication SP-666.

[4] International Ocean Colour Coordinating Group (IOCCG). (2000). Remote sensing of ocean colour in coastal, and other optically-complex waters, p. 140. IOCCG.

[5] Ruddick, K., G. Lacroix, C. Lancelot, B. Nechad, Y. Park, S. Peters, and B. Van Mol. (2008). Optical remote sensing of the North Sea, p. 79-90. *In* V. Barale and M. Gade [eds.], Remote sensing of the European Seas. Springer-Verlag.

[6] Robinson, I. S., D. Antoine, M. Darecki, P. Gorringe, L. Pettersson, K. Ruddick, R. Santoleri, H. Siegel, P. Vincent, M. R. Wernand, G. Westbrook, and G. Zibordi. (2008). Remote sensing of shelf sea ecosystems: state of the art and perspectives, p. 60. European Science Foundation Marine Board.

[7] Gohin, F., B. Saulquin, H. Oger-Jeanneret, L. Lozac'h, L. Lampert, A. Lefebvre, P. Riou, and F. Bruchon. (2008). Towards a better assessment of the ecological status of coastal waters using satellite-derived chlorophyll-a concentrations. Remote Sensing of the Environment **112**: 3329-3340.

[8] Stumpf, R. P., and M. C. Tomlinson. (2005). Remote sensing of harmful algae blooms. *In* R. Miller, C. D. Castillo and B. McKee [eds.], Remote sensing of coastal aquatic environments: technologies, techniques and applications. p277-296, Kluwer.

[9] Ruddick, K., G. Lacroix, Y. Park, V. Rousseau, V. De Cauwer, and S. Sterckx. 2008b. Overview of Ocean Colour: theoretical background, sensors and

applicability for the detection and monitoring of harmful algae blooms, p. 331-383. Real-time coastal observing systems for marine ecosystem dynamics and harmful algal blooms. Oceanographic Methodology Series. UNESCO publishing.

[10] Lancelot, C. (1995). The mucilage phenomenon in the continental coastal waters of the North Sea. Science of the total Environment 165: 83-102.

[11] Moll, A., and G. Radach. (2003). Review of three-dimensional ecological modelling related to the North Sea shelf system Part 1: models and their results. Progress in Oceanography **57:** 175-217.

[12] Lancelot, C., Y. Spitz, N. Gypens, K. Ruddick, S. Becquevort, V. Rousseau, G. Lacroix, and G. Billen. (2005). Modelling diatom and *Phaeocystis* blooms and nutrient cycles in the Southern Bight of the North Sea: the MIRO model. Marine Ecology Progress Series **289:** 63-78.

[13] Lacroix, G., K. Ruddick, Y. Park, N. Gypens, and C. Lancelot. (2007). Validation of the 3D biogeochemical model MIRO&CO with field nutrient and phytoplankton data and MERIS-derived surface chlorophyll *a* images. Journal of Marine Systems **64(1-4):** 66-88.

[14] Borges, A. V., and M. Frankignoulle. (1999). Daily and seasonal variations of the partial pressure of CO2 in surface seawater along Belgian and southern Dutch coastal areas. Journal of Marine Systems **19**: 251-266.

[15] Gypens, N., C. Lancelot, and A. Borges. (2004). Carbon dynamics and CO2 air-sea exchanges in the eutrophied coastal waters of the Southern Bight of the North Sea: a modelling study. Biogeosciences **1:** 147-157.

[16] Lefèvre N., J. Aiken, J. Rutllant,G. Daneri, S. Lavender & T. Smyth (2002). Observations of pCO2 in the coastal upwelling off Chile: Spatial and temporal extrapolation using satellite data, Journal of Geophysical Research, 107 (C6), doi:10.1029/2005GL023942

[17] Lohrenz S.E. & W.-J. Cai (2006). Satellite ocean color assessment of air-sea fluxes of CO2 in a river-dominated coastal margin, Geophysical Research Letters, 33, L01601, doi:10.1029/2005GL023942

[18] Olsen A., J.A. Trinanes & R. Wanninkhof (2004). Sea–air flux of CO2 in the Caribbean Sea estimated using in situ and remote sensing data, Remote Sensing of Environment **89**: 309–325

[19] Borges, A., K. Ruddick, L.-S. Schiettecatte, and B. Delille (2008). Net ecosystem production and carbon dioxide fluxes in the Scheldt estuarine plume. BMC Ecology **8**, 15, doi:10.1186/1472-6785-8-15.

[20] Platt, T., Fuentes-Yaco, C., & Frank, K.T. (2003). Spring algal bloom and larval fish survival, Nature **423**: 398-399.

[21] Park, Y., and K. Ruddick. (2007). Detecting algae blooms in European waters. ENVISAT symposium. European Space Agency SP-636.

[22] Laran, S. and A. Gannier. (2008). Spatial and temporal prediction of fin whale distribution in the northwestern Mediterranean Sea. ICES Journal of Marine Science, **65**, 1-10.